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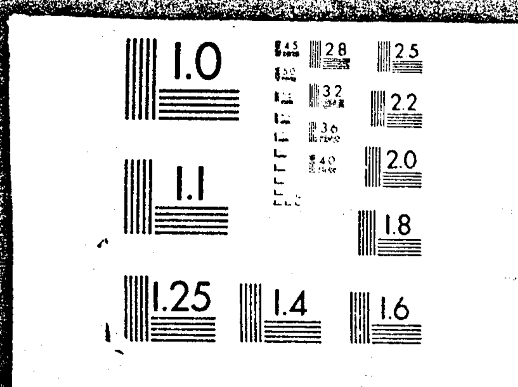

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FLYWHEEL ROTOR AND CONTAINMENT
TECHNOLOGY DEVELOPMENT

S. V. Kulkarni

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Lawrence
Livermore
Laboratory

PROJECT SUMMARY

Project Title: Flywheel Rotor and Containment Technology Development

Principal Investigator: S. V. Kulkarni

Organization: Lawrence Livermore National Laboratory

Project Goals:

- To develop, by FY1984, an economical and practical composite flywheel having an energy density of 88 Wh/kg at failure, an operational energy density of 44 to 55 Wh/kg, and an energy storage capacity of approximately 1 kWh.
- To determine the suitability of various manufacturing processes for low-cost rotor fabrication.
- To investigate flywheel and flywheel-systems dynamics.
- To test and evaluate prototype rotors for use in transportation and stationary applications.
- To develop, by FY1984, a fail-safe, lightweight, and low-cost flywheel containment.

Project St tus: The following tasks have been accomplished:

- Evaluation and selection of 1-kWh, first-generation, advanced flywheel rotor designs for subsequent development towards the DOE-established energy density goal of 88 Wh/kg at burst. (Task Milestone).
- Completion of an advanced design concept for a flywheel primary containment structure, capable of containing the failure of a 1-kWh flywheel rotor and targeted for vehicular applications (Task Milestone).
- Non-destructive inspection and burst testing of approximately twenty (20) prototype rotors, and initiation of cyclic testing.
- Completion of various activities in the areas of rotor manufacturing processes, dynam.. analyses and composite materials design data generation.
- Initiation of an economic feasibility study to establish a rational costing methodology for composite rotors and containment.

Contract Number: W-7405-Eng-48

Contract Period: October 1, 1980 to September 30, 1981

Funding Level: $926,000

Funding Source: U.S. Department of Energy

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FLYWHEEL ROTOR AND CONTAINMENT TECHNOLOGY DEVELOPMENT*

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ABSTRACT

The status of the flywheel rotor and containment technology development program during FY81 is reviewed in this paper. The specific objectives of the different activities are delineated, and progress during the present reporting period is described briefly. Because of the current emphasis in certain areas such as flywheel cost analysis, rotor dynamics, testing, and containment development, accomplishments in those areas during FY81 are reported separately.

INTRODUCTION

With the increased emphasis on energy conservation and fuel economy, the development of energy-storage devices has gained considerable momentum. These devices accomplish load leveling, power boost, and energy recovery. Flywheels are one such method of energy storage that has received increasing attention in the past few years. It has been concluded that incorporating a flywheel in a vehicle that operates predominantly in urban driving situations will result in significant fuel savings. Flywheels also have potential applications in various fixed-base application, such as wind- and solar-energy generation and utility load leveling. While the flywheel is not a new concept, the use of fiber-reinforced composite materials in a flywheel is. These materials possess high specific stiffness and strength, the latter being a direct measure of the specific energy of the flywheel rotor. The high specific strength enables fiber-reinforced composite rotors to have higher energy-storage efficiency than metallic rotors. It has also been demonstrated that fabrication costs for composite material components are lower than their metallic counterparts in many cases. In addition, failures in composites are generally less catastrophic, thus, requiring lighter containment structures.

The two primary objectives of this effort are:

- To develop an efficient, economical, and practical composite flywheel having an energy density of 88 Wh/kg (40 Wh/lb) at failure, with an operational range of 44 to 55 Wh/kg (20 to 25 Wh/lb) and an energy-storage capacity of approximately 1 kWh.

- To develop a fail-safe, lightweight, and low-cost composite containment for the flywheel.

The strategy being followed to achieve the objectives is outlined below:

- Design, develop, fabricate, and test the most promising generic rotor and containment concepts.

- Use existing technologies wherever applicable.

- Initiate effort, as needed, to support pertinent technology areas.

- Seek active participation by industry, national laboratories, and universities to (1) use expertise in an optimum fashion, (2) promote cross fertilization of ideas, and (3) create a competitive environment.

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*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

The highlights of the accomplishments for this task during FY81 are:

• Completed the evaluation of prototype flywheels and identification of promising designs for further development and testing (Task Milestone).

• Evaluated the Flywheel Programs in W. Europe for DOE.

• Prepared a multi-year plan (1981-85) for Flywheel Rotor and Containment Technology Development.

• Attained highest energy density for any flywheel rotor to date (36.1 Wh/lb for the Garrett AiResearch design).

• Obtained highest energy density for a laminated composite flywheel rotor (30.5 Wh/lb for LLNL design).

• Obtained highest energy capacity for any composite flywheel (1.94 kWh for the Rocketdyne design).

• Initiated a study for the cost analysis of composite flywheels.

• Used ultrasonic and radiographic techniques at LLNL for nondestructive inspection of all prototype flywheels.

• Spin-tested to failure approximately twenty (20) prototype flywheels. Test data are the most comprehensive to date. Many failures were both repeatable and predictable Understanding of failure modes has considerably enhanced our understanding of the containment process.

• Developed a preliminary cyclic test plan at LLNL for composite rotors for establishing relationship between short-term spin tests and long-term service performance.

• Fabricated and tested steel and aluminum/Kevlar-29 cloth containment rings for the six prototype rotors.

• Completed two competitive containment design studies.

Specific objectives and the status for different activities are discussed in the following pages.

OBJECTIVES AND STATUS OF VARIOUS ACTIVITIES

The work breakdown structure of this task consists of eight (8) major subtasks and several activity areas under each subtask. Because of the current emphasis in certain areas such as flywheel cost analysis, rotor dynamics, testing, and containment development, progress during FY81 is reported separately.

1. Technical Management, Lawrence Livermore National Laboratory (LLNL)--Technical management activities play a crucial role because of the various industry and university subcontracts and the interdisciplinary nature of this task.

Objectives:

• To identify activities and projected costs with the Task goals and the availability of funding.

• To prepare IFPs and evaluate responses.

• To evaluate technical performance and track contract schedules and milestones.

- To provide consultation to industry.

- To promote technology transfer.

Status:

- Planned, coordinated, and directed approximately twenty five (25) activities at LLNL, other national laboratories, industry, and universities.

- Evaluated the Flywheel Programs in W. Europe for DOE.

- Prepared a multi-year plan (1981-85) for Flywheel Rotor and Containment Technology Development.

- Completed the evaluation of prototype flywheels and identification of promising designs for further development and testing. Decision analysis techniques were utilized in the evaluation process (Task Milestone).

While the ultimate decision-making responsibility rested with LLNL, a Rotor Selection Committee comprised of experts from various technology/application areas was formed to facilitate the decision-making process. The committee was formed because of the need to address many different and diverse issues such as performance, costs, systems adaptability, development risks, etc.

Based on the various selection criteria and the rankings, the following recommendations were made:

- Further development and testing of (a) the Garrett multi-material multi-ring rim rotor, and (b) the constant thickness laminated disk rotor with and without a rim (LLNL and GF designs) should be continued.

Since the GE and LLNL designs are generically similar, development of these two concepts under a single activity is justifiable.

- As an option, since the Avco rotor design was ranked highly, a prototype should be fabricated and spin-tested to assess its potential.

Figure 1 illustrates the Garrett, LLNL, GE, and the proposed Avco designs.

2. Composite Laminated-Disk Rotor Technology Development (LLNL)

Objectives:

The two primary objectives are:

- To develop the technology for high-energy-density, fiber-composite flywheels based on the laminated-disc concept.

- To demonstrate a prototype of this design for a practical flywheel.

The specific tasks for FY81 are:

- To conduct stress analysis and optimization studies of laminated disk/ring type flywheels.

- To develop a cyclic test plan for rotors.

- To establish NDI procedures, and evaluate the effect of defects on rotor performance.

- To generate design data for elastomeric bond.
- To develop a biaxial stress test fixture.

Status:

- Both constant and tapered thickness S2-glass and graphite/epoxy laminated disks designed and fabricated by LLNL were spin-tested to failure at Applied Physics Laboratory (APL) and Oak Ridge Flywheel Evaluation Laboratory (ORFEL). The constant-thickness S2-glass/epoxy disk had an energy density of 30.5 Wh/lb at burst.

- Stress analysis and optimization studies were conducted for chopped fiber S2-glass/polyester sheet molding compound (SMC) molded disk/filament-wound graphite/epoxy ring hybrid rotors. The effect of ring radial thickness and cross-section shape (such as trapezoidal, exponential, etc.) on energy density was investigated. The disks were fabricated by Owens-Corning, and the rings by Lord Kinematics.

- For the rotor cyclic test plan, see "Composite Flywheel Durability and Life Expectancy: Test Program," by K. L. Reifsnider, S. V. Kulkarni, and D. M. Boyd, in this meeting.

- Ultrasonic and radiographic NDI was conducted for various prototype rotors before testing them at APL and ORFEL.

- Limited static and fatigue data in torsion were obtained for the rotor/hub elastomeric bond. The bonding technique which utilizes a urethane elastomer instead of the natural rubber/adhesive combination was developed at LLNL.

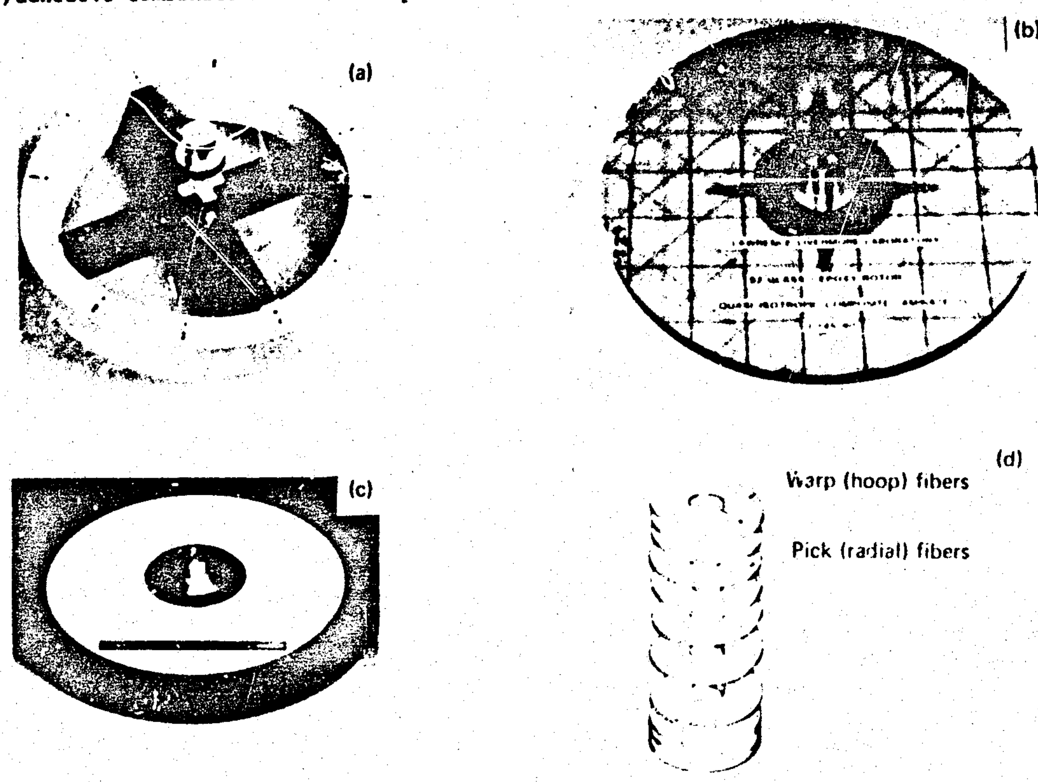

Fig. 1. Flywheel Designs Identified for Further Development and Testing. (a) Garrett Multi-Material, Multi-Ring Flywheel. (b) LLNL Disk-Type Flywheel. (c) General Electric Disk-Rim Hybrid Flywheel. (d) Avco Bidirectional Weave Flywheel Concept.

• The biaxial test fixture was fabricated and tests were performed for circular composite laminate specimens. Test results indicate that modifications to the loading and gripping mechanism will be required.

A detailed description of the LLNL activities is given in Refs. 1 and 2.

3. Advanced Rotor Concepts--Industry

a. Alpha-Ply Composite Laminated Disk/Ring Hybrid Rotor Development (GE)

Objectives:

• To design and fabricate two (2) prototype alpha-ply S2-glass/epoxy laminated disk/filament-wound graphite/epoxy hybrid flywheels.

• To perform analytical studies in the areas of disk/ring optimization, fatigue and creep effects, and hub attachment designs.

Status:

• This effort has been completed (Ref. 3).

• The design and fabrication of the two (2) prototype flywheels and the analytical studies were completed during FY81.

• Burst tests of the GE prototype flywheels at APL yielded a maximum energy density of 25.6 Wh/lb.

• One (1) prototype was fatigue-tested at ORFEL.

b. Bidirectional Weave Composite Rotor Materials Evaluation (Avco)

Objectives:

• To conduct optimization studies for the S2-glass bidirectional weave by altering the ratio of the percentages of radial and hoop fibers as a function of disk radius.

• To evaluate the potential of bidirectionally (radial and hoop) woven composite materials for flywheel application by weaving sample laminates and conducting tests to obtain the pertinent mechanical properties.

Status:

• This effort has been completed (Ref. 4).

Also see "Circular Weave Flywheel Materials Evaluation and Composite Flywheel Burst Containment," by A. Sapowith and W. Handy in this meeting.

c. Development of Metglas Flywheel--Applied Physics Laboratory (APL)

Objectives:

• To design, fabricate, and test subscale and prototype wound Metglas ribbon rotors.

Status:

• This activity is complete (Ref. 5).

• Four (4) 50-Wh and two (2) 200-Wh Metglas prototype rotors were fabricated and tested. The rotors were wound from nominal 2-mil-thick Metglas amorphous metal ribbon on a

four-sp aluminum hub. A maximum energy density of 9 Wh/lb was obtained at burst for the prototyp .

d. Advanced, 1-kWh "State-of-the-Art" Prototype Rotor Development (Garrett AiResearch)

Objectives:

- To design, fabricate, and deliver ten (10) multi-material, multi-ring prototype rotors having an energy capacity of up to 1 kWh and a maximum energy density of 40 Wh/lb at burst and an operational energy density of 20-25 Wh/lb.

Status:

- A subcontract has been placed with Garrett for design and fabrication of ten (10) prototype rotors. The development effort will involve minor design modifications of the existing graphite/epoxy hub.

e. Prototype Rotor Development for Vehicular Applications (GE)

Objectives:

- To design, fabricate, and deliver nineteen (19) laminated disk/filament-wound rim hybrid prototype rotors having performance goals consistent with vehicular application requirements.

Status:

- A subcontract has been placed with General Electric for the design and fabrication of nineteen (19) prototype flywheels.

4. Composite Rotor Manufacturing Technology Development

a. Compression-Molded Energy-Storage Flywheels (Owens-Corning)

Objectives:

- To develop chopped S2-glass/polyester SMC (sheet molding compound) having an ultimate tensile strength of 45 ksi.
- To develop the processing technology required to mold 1-in. thick SMC parts.
- To mold constant- and tapered-thickness SMC flywheels in a single step.

Status:

- This activity is complete (Ref. 6).
- Tensile strengths of up to 45 ksi (the highest to date) were obtained for chopped S2-glass/polyester SMC.
- A fabrication process was developed for molding thick SMC laminates and successfully molding 21-in.-diam, 1-in.-thick constant- and tapered-thickness disks.
- Burst tests of the SMC molded disk graphite/epoxy ring hybrid rotors at APL and ORFEL yielded an energy density of 14·7 Wh/lb at failure.

b. Fabrication of High-Performance Filament-Wound Fiber Composite Rings (Lord Kinematics)

Objectives:

- To filament-wind rings (graphite, Kevlar-49/epoxy, and hybrid) of rectangular and trapezoidal cross section for SMC molded disk/ring hybrid rotors.

- To explore the utilization of SiC whiskers as matrix reinforcement in the filament winding process.

- To assemble, by a "shrink-fit" approach, the SMC molded disk/ring hybrid rotors.

Status:

- Twelve (12) graphite/epoxy rings (21-in. i.d.) with and without SiC whisker reinforcement were filament-wound.

- Five (5) constant-thickness SMC molded disk/ring hybrid rotors were assembled by the "shrink-fit" approach. Two of these rotors have been burst-tested at APL and ORFEL.

c. Composite Flywheel Fabrication and Process Optimization (Ewald Associates)

Objectives:

- To define and optimize the compression molding technique to fabricate laminated disk/filament-wound rim flywheels in a single step.

- To fabricate and deliver six (6) flywheels for testing and evaluations.

- To fabricate ten (10) graphite/epoxy composite hubs for the Garrett prototype flywheel.

Status:

- A subcontract has been placed with Ewald Associates.

d. Composite Rotor and Containment Cost Analysis (Battelle-Columbus)

Objectives:

- To develop a costing methodology to establish the cost range as a function of rotor and containment design, materials, manufacturing process, and production quantities.

Status:

- A subcontract was placed with Battelle-Columbus Laboratories. Also see "The Approach for Manufacturing Cost/Design Trade Studies for Flywheels," by B. Noton in this meeting.

5. Investigation of Flywheel and Flywheel Systems Dynamics

a. Dynamics of Composite Material Flywheels (Univ. of Oklahoma)

Objectives:

- To perform continuum analysis of various generic composite-material flywheel rotors and a system analysis of the rotor system to obtain natural frequencies for various vibrational modes.

Status:

- This task is partially complete (Ref. 7). Also see "Design Guide for Composite Material Flywheels (Dynamics)," by C. W. Bert in this meeting.

b. Dynamic Analysis of Bonded Multi-Disk Assemblies (Probeck Associates)

Objective:

- To investigate the dynamic characteristics of bonded multiple-disk flywheel assemblies in order to understand the effects of bond thickness and radius, and aspect ratio of the assembly.

Status:

- This study has been completed (Ref. 8). Important conclusions of this analysis are: (1) transverse, torsional, and out-of-plane whirl modes exist within the operating speed range, (2) natural frequencies increase with the square root of Young's Modulus of the elastomeric bonding material.

6. Fiber-Composite Flywheel Rotor Design Data

a. Failure Analysis of Composite Laminate Flywheels (Villanova Univ.)

Objective:

- To develop a laminate-failure analysis code which incorporates bilinear stress-strain behavior, and compare failure predictions from the code with test data.

Status:

- This study has been completed (Ref. 9). A computer code called BILAM was developed. This code performs laminate-failure analysis using bilinear stress-strain approximations of the nonlinear stress-strain curves. Predictions of laminate failure stresses made with this code correlate better with experimental results.

b. Tension-Tension Fatigue Tests of Unidirectional S2-Glass/Epoxy Laminates (Boeing-Vertol)

Objectives:

- To generate fatigue design data for filament-wound unidirectional S2-glass/epoxy laminates.

- To investigate effects of frequency, stress ratio, and cyclic loading wave shape.

Status:

- This activity has been completed and a report prepared (Ref. 10). S-N curves and residual strength data have been obtained for two load ratios simulating the spin-up and spin-down deep cycles and the stop and go shallow cycles, respectively.

The following observations can be made from these data: (1) cycles to failure decrease with increasing cyclic rate, and (2) a square wave pattern significantly reduces cyclic life, as compared to a smoother sine-wave load spectrum.

c. Tension-Tension Fatigue Tests of Unidirectional Kevlar-29/Epoxy Laminates (GE)

Objectives:

- To generate fatigue design data for filament-wound unidirectional Kevlar-29/epoxy laminates.

- To investigate effects of frequency, stress ratio, and cyclic loading wave shape.

Status:

This effort has been completed and a final report written (Ref. 11). Static and limited fatigue data were obtained. Problems associated with tab failures in the specimens prevented the attainment of all the objectives.

7. Test and Evaluation of Prototype Rotors

a. Burst and Cyclic Testing of Prototype Rotors (ORFEL)

Objectives:

- Burst tests of one (1) LLNL and one (1) GE prototype rotor.
- Follow-up tests for Rocketdyne Prototype No. 1 rotor.
- Burst tests of two (2) Owens-Corning/Lord rotors.
- Fatigue tests of GE disk/ring prototype and Garrett single-rim rotors.

Status:

- This activity is partially complete. Some results of this test program are given in Table 1. See Ref. 12 and "Rotor Testing in FY81," by R. S. Steele in this meeting.

b. Spin-Testing of Prototype Rotors (APL).

Objective:

- To burst-test ten (10) prototype rotors supplied by LLNL.

Status:

- This test program has been completed (see Ref. 13). Ten (10) rotors which included the LLNL constant and tapered thickness laminated disk, GE laminated disk/ring, Owens-Corning/Lord molded disk/ring, and Brobeck designs were tested during FY81. Some of the results of the tests are tabulated in Table 1.

c. Spin-Testing of Rocketdyne RPE-10 Flywheel with Fixed Bearing Supports (Rocketdyne)

Objective:

- To perform nine spin tests of the Rocketdyne Prototype Rotor No. 2 to operating speed with a fixed bearing suspension system.

Status:

- The test has been completed (Ref. 14). The stated objective was not met because the flywheel failed at the first full speed run at 21,500 rpm. The most probable reason for the failure was the separation of the overwrap due to increase of temperature in the spin test chamber to about 260°F.

8. Development of Flywheel Containment

a. Rotor Containment Concept Development (GE)

Objective:

- To design a lightweight, fail-safe, and low-cost containment concept for generic rotor designs.

TABLE 1. Advanced Rotor Designs and Maximum Energy Densities.

	Design	Test Facility	Materials	Maximum energy density Wh/lb (kWh)
1	Garrett multi-material, multi-ring rim	ORFEL	Kevlar-49/-29/S2-glass rings/graphite hub	36.1 (1.23)
2	Brobeck multi-material rim with tension-balanced spokes	APL	S2-glass/Kevlar-49 ring, Kevlar-29 spokes, Al/Kevlar-49 hub	28.9 (0.71)
3	Rocketdyne rim with overwrap and twin-disk hub	ORFEL	Graphite/Al hub	16.4 (1.94)
4	Hercules contoured rim	ORFEL	Graphite/Al hub	17.0 (0.85)
5	GE alpha-ply laminated disk with rim	APL	S2-glass disk/graphite ring/Al hub	25.6 (0.283)
6a	LLNL tapered-thickness laminated disk	APL	Graphite/Al hub	28.4 (0.31)
6b	LLNL constant-thickness laminated disk	APL	Graphite/Al hub S2-glass/Al hub	23.00 30.5 (0.157)
7	LLNL/OC/Lord Molded disk with rim	APL	S2-glass SMC disk/graphite ring/Al hub	14.7 (0.419)
8	APL Metglas ribbon rim	APL	Metglas rim/Al hub	9.00 (0.039)

Status

- This activity has been completed (Ref. 15). Also see "Flywheel Housing Design Concept Development," by A. P. Coppa in this meeting.

Figures 2 and 3 illustrate the containment rings designed by GE for the Garrett and the LLNL tapered disk flywheels.

b. Composite Flywheel Containment Design Study (Avco)

Objective:

- To design a lightweight, fail-safe, and low-cost containment concept for generic rotor designs.

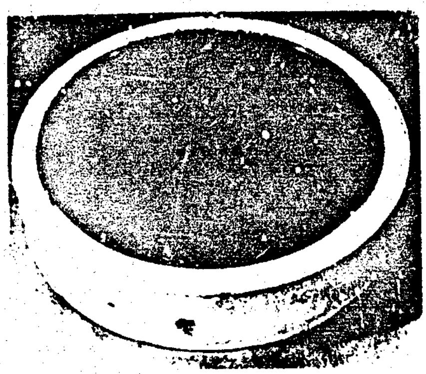

Fig. 2. Containment Ring for Garrett Rotor (aluminum liner overwrapped with dry, woven Kevlar fabric).

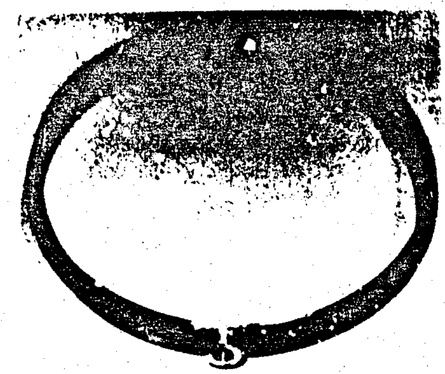

Fig. 3. Steel Containment Ring for LLNL Rotor.

Status:

- This activity has been completed (Ref. 16). Also see "Circular Weave Flywheel Materials Evaluation and Composite Flywheel Burst Containment," by A. Sapowith and W. Handy in this meeting.

CONCLUSIONS

In summary, an overview of the flywheel rotor and containment technology development effort during FY81 has been presented. That this effort encompasses a broad spectrum of technologies is obvious. Every effort is being made to use state-of-the-art techniques and advance them, if necessary, to accomplish the task objectives. The assessment is that significant progress has been made during the present reporting period and that it is indeed feasible to develop adequate rotor and containment designs suitable for both transportation and stationary applications.

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